Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 40, Part 4, No. 352, December, 1990

Discharge of Suspended Sediment and Solutes from a Hilly Drainage Basin in Devon, UK, as Analysed by a Cascade Tank Model

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(Manuscript received on July 31, 1990)

Abstract

The discharge of suspended sediment and two solutes from the River Dart basin (46 km^2) have been analysed by correlation with different runoff components. The cascade tank model, developed by Suzuki et al.[1] to simulate the hydrologic response of different soil horizons in Japanese basins in mountainous headwaters, proved appropriate for separating the hydrographs of the River Dart into direct runoff, throughflow and baseflow components. Similarity in the topography and the properties of the weathered mantle, and in the occurrence of saturation overland flow in only limited parts of the basin are thought to produce hydrological similarities between the River Dart basin and small mountainous basins in Japan.

Because suspended sediment concentrations are low and nearly constant in the absence of direct runoff, excess sediment discharge during rain storms is ascribed to direct runoff. The concentrations of suspended sediment in direct runoff is high at the beginning of storm runoff, but quickly decreases to a lower and nearly constant level.

Multiple regression analysis has been used to reveal the contribution of different runoff components to the discharge of magnesium and nitrate ions, assuming that each runoff component is characterised by distinctive concentrations of these solutes. The concentration of magnesium ion is greater in runoff originating from deeper circulation. Although the magnesium ion concentrations in individual runoff components are almost constant, those of nitrate are highly variable from storm to storm and throughout the year. Nitrate concentrations in throughflow are greater than in baseflow on many occasions. It is suggested that the nitrate concentration in each runoff component increases or decreases during a storm event, according to transient mineralisation and leaching in the pertinent soil horizon.

1. Introduction

The hydrological application of the tank model was first proposed by Sugawara[2]. Use of a cascade of tanks to simulate different runoff components in the headwaters of a drainage basin was later proposed by Ishihara and Kobatake[3]. More detailed examination of the cascade tank model was carried out by Suzuki et al.[1] to improve the simulation of the hydrologic response of different soil horizons and to make use of it for the prediction of surficial landslides and consequent debris flows. Okunishi et al.[4] have shown that the model developed by Suzuki et al.[1] is widely applicable to small basins where channel storage effects are negligible. A tank model applicable to British rivers has been proposed by Hata and Anderson[5]. Their study focused on larger drainage basins and the storage effects of slopes and streams are represented by lumped parameters, which are difficult to separate. It is, therefore, not practical to apply their model directly to small drainage basins in Britain.

Relationships between the concentration of suspended sediment or dissolved material and the water discharge have been studied for many years. Regression analysis have proved one of the most popular approaches to the prediction of water quality. Walling[6)] and Walling and Webb[7)] have examined the precision and reliability of such water quality predictions on the basis of their observations in Britain.

More detailed analysis of the relationship between water quality and the hydrologic condition of a drainage basin is, however, needed, since the source of the suspended and dissolved material is frequently localised in particular parts of the drainage basin, and their transport is related to specific runoff components. Seasonal change in the regression relationship is significant in some Japanese drainage basins[4)]. It is thus suggested that the mode of release of the material from the catchment will vary according to the hydrological and other conditions.

If all the suspended load in river water is derived from the erosion of slope surfaces, surface runoff and raindrop impact will be the major agents of sediment production. Another possible mechanism for supplying fine sediment particles to streamflow is provided by the remobilisation of armoured deposits such as point bars which are formed by high magnitude floods, and by the erosion of stream banks. In these cases, the total runoff is responsible for mobilising and transporting suspended sediment. Although attempts have been made to determine the source of suspended sediment using the fingerprint technique (Peart and Walling[8)]), there remains a need to improve the theory of suspended load production through quantitative analysis of the dependence of suspended load on different runoff components.

It has been recognised that different runoff components may be characterised by distinctive concentrations of dissolved material. The simplest theory is that baseflow contains a constant concentration of dissolved substances and that this is diluted by the direct runoff to produce temporal changes in the final concentration in the river water. This model provides a basis for separating direct runoff and baseflow within a hydrograph using the hydrochemical approach (Dinçer[9)]). Another approach has been proposed by Oba[10)] who assumes that each runoff component possesses a characteristic concentration of differrent dissolved substances. The characteristic concentration can be determined through regression analysis, if runoff is separated into its individual components by an appropriate method. Okunishi et al.[4)] applied this method to a small mountain drainage basin underlain by Paleo-Cenozoic sedimentary rocks. Their results indicated that the solute concentration associated with each runoff component is not constant throughout a rain storm, and that it will also vary seasonally. More detailed analysis of the dynamics of solute production associated with different runoff components is thus needed to provide a better understanding of the hydrological processes involved.

In this paper, relationships between water discharge and suspended sediment and solute (magnesium and nitrate) concentrations estabalished for the River Dart basin, UK are examined using runoff compoennt analysis based on a cascade tank model. The results are compared with a similar analysis undertaken in a Japanese drainage basin. The hydrological processes associated with the occurrence of different runoff components and their suspended and dissolved loads are discussed.

2. Study area

The River Dart is a small (46 km^2) tributary of the River Exe in Devon, UK, underlain by Carboniferous slates and Triassic sandstones, the latter being restricted to the headwaters of the main channel. The mean annual precipitation and runoff for the basin are 1,050 mm and 550 mm, respectively.

The topography of the basin is shown in **Fig. 1**. The relief and slope inclination are

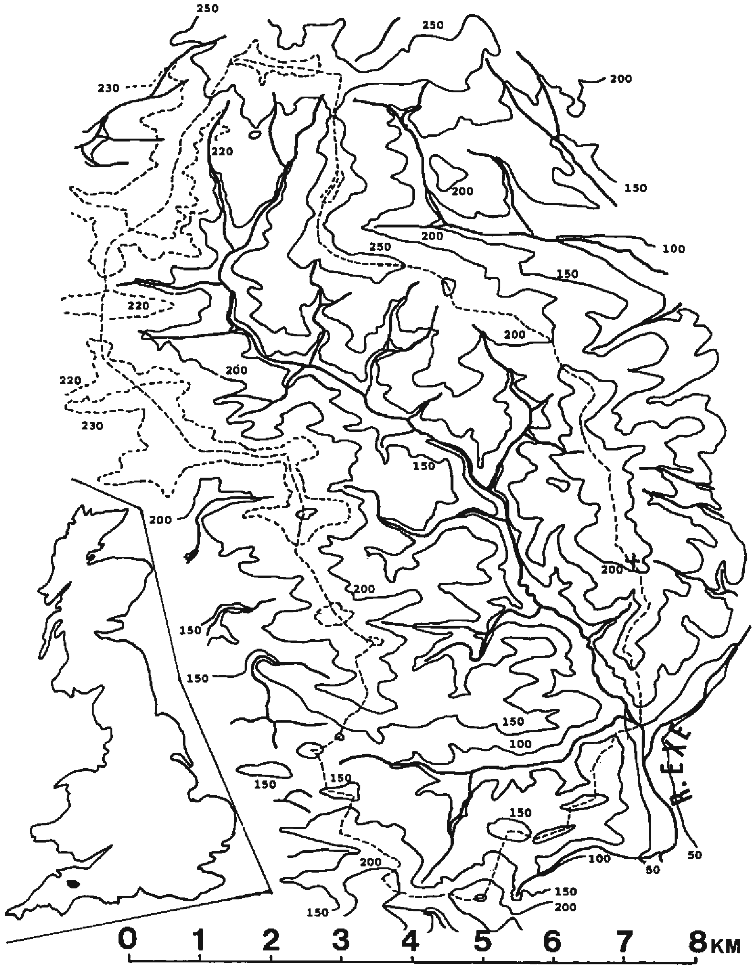

Fig. 1. The River Dart basin above its confluence with the River Exe. The location of the rain gauge is indicated by '+'.

greater in the Carboniferous portion than in the Triassic zone. Most slopes exhibit convex-concave profiles which are common in Devon[11], although concave segments are limited to the vicinity of the narrow valley floors. The weathered mantle is commonly stratified as a result of solifluction activity during the Pleistocene (Cullingford[11]) and biological activity during the Holocene, although the total depth is usually between 0.5 m and 2 m (Grainger[12]). Most of the area is occupied by pasture and arable land. The gauging station at the outlet of the basin is operated by the University of Exeter. River stage is recorded and calibrated to discharge. Concentrations of suspended sediment and several solutes are also measured by water sampling.

A topographic map of the River Ishida basin (23.4 km^2) in which Okunishi et al.[4] have carried out similar research is shown in **Fig. 2**. The bedrock is Permo-Triassic sedimentary strata, dominated by slates. Relief energy and slope angle are much greater than in the River Dart basin, and so-called zero order valleys (Tsukamoto[13])

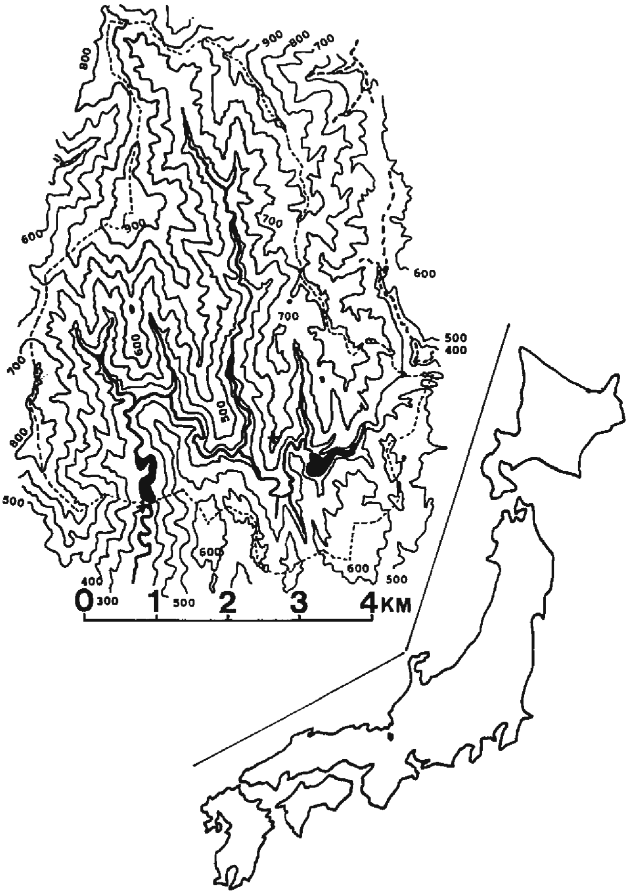

Fig. 2. The River Ishida basin above the Ishida-gawa dam. The location of the rain gauges is indicated by '+'.

occur on both sides of the first order valleys. However, the depth and structure of the weathering mantle as described by Okunishi and Okamoto[14] are very similar to those in the River Dart basin. This basin is fully covered with forest with the exception of roads and rivers. The discharge at the Ishidagawa dam and the rainfall at two sites (see **Fig. 2**) are monitored by the Ishidagawa Dam Office. River water was sampled at the inlet to the dam[4] between 1982 and 1984, for the concentrations of suspended sediment and solutes.

3. The cascade tank model

As mentioned above, the cascade tank model was developed to simulate the behaviour of water in different soil horizons on hillslopes. In many cases, a cascade of three tanks is used. These represent the water storage in different soil horizons and generate the runoff which corresponds to direct runoff, throughflow and baseflow, respectively. **Fig. 3** shows the fundamental structure of the tank model that has been proposed by Suzuki et al.[1] and which has been applied to the River Dart basin. Rainfall is introduced into the top tank with a cross sectional area of unity, so that 1 mm of rainfall causes an increment of water level of 1 mm if no outflow occurs. Outflow does, however, occur, lateral flow being represented by discharge through the side outlets and

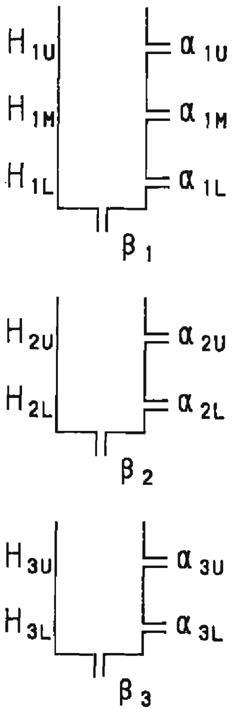

Fig. 3. Structure of the tank model of Suzuki et al.[1].

percolation to the underlying horizon by discharge through the bottom outlet. The discharge through any outlet is assumed to be proportional to the hydraulic head or to the water level relative to the height of the outlet. The behaviour of the other tanks is similar, but evapotranspiration may be represented by discharge through the bottom outlet of the bottom tank or by constant rate uptake from the bottom tank.

With the symbols as defined in **Fig. 3**, the water balance of the three tanks for rainfall of intensity p may be written as

$$dH_1/dt=p-q_1-f_1 \tag{1}$$

$$dH_2/dt=f_1-q_2-f_2 \tag{2}$$

$$dH_3/dt=f_2-q_3-f_3 \tag{3}$$

$$q_1=\alpha_{1U}\xi(H_1-H_{1U})+\alpha_{1M}\xi(H_1-H_{1M})+\alpha_{1L}\xi(H_1-H_{1L}) \tag{4}$$

$$q_2=\alpha_{2U}\xi(H_2-H_{2U})+\alpha_{2L}\xi(H_2-H_{2L}) \tag{5}$$

$$q_3=\alpha_{3U}\xi(H_3-H_{3U})+\alpha_{3L}\xi(H_3-H_{3L}) \tag{6}$$

$$f_1=\beta_1 H_1 \tag{7}$$

$$f_2=\beta_2 H_2 \tag{8}$$

$$f_3=\beta_3 H_3 \tag{9}$$

where

$$\xi(x)=\begin{cases} x & (\text{if } x\geqq 0) \\ 0 & (\text{if } x<0) \end{cases} \tag{10}$$

and H_n and q_n ($n=1, 2, 3$) denote the water level and specific discharge of the n'th tank, respectively. The quantities q_1, q_2 and q_3 represent the specific discharge of the direct runoff, throughflow and baseflow, respectivey.

Equations (1)-(9) are replaced with difference equations with a time step Δt (fixed to 1 hour in all cases considered here) to obtain a numerical solution. The explicit method has been adopted to solve the difference equations, although the implicit method has been partly introduced to improve the convergence of the solution. Because Eqs. (1)-(3) represent the water balance, the simulation obtained from the tank model automatically satisfies the water balance. The values of the parameters are determined by trial-and-error, by comparing the simulated hydrograph with the observed one. The tank model produced by Suzuki et al.[1] does, however, have the advantage of allowing some systematic calibration, because the time constants of the tanks are largely determined by the β values, and are greater for the lower tank. After α_3's and β_3 are determined from the effective rainfall and the baseflow recession curve, the values of β_1 and β_2 are tentatively determined from the recession characteristics of direct runoff and throughflow, respectively. Then α_1's and α_2's are adjusted to simulate the shape of the hydrograph peaks and the subsequent recession (or the secondary peaks due to throughflow). Then the adjustment of all parameters is repeatedly carried out so that the detailed structure of the observed hydrographs is matched by the calculated hydrographs. Another advantage of the model described by Suzuki et al.[1] is that it is easy to decide which parameter to modify when a particular portion of a calculated hydrograph is to be improved.

Hydrographs involving different values of peak discharge and of different time scales should be analysed to obtain unique estimates of the parameters. A multi-peaked hydrograph is often very useful for fine adjustment of the parameters. Optimisation of the parameters using a main-frame computer procedure has been proposed, e.g. by Nagai and Kadoya[15], but this procedure was not adopted here.

4. The tank model as fitted to the River Dart basin

Fifteen storm events were selected from the hydrological records of the River Dart for the period 1982–1984. The available data comprised time series of rainfall, runoff and the concentration of suspended sediment, magnesium and nitrate with a time step of one hour.

Evapotranspiration (the annual total being about 500 mm) was ignored in the analysis since, over the period of 96 hours involved, it was much smaller than the observed rainfall. Thus the value of β_3 was assumed to be zero, and the values of α_{3L} were determined from the recession curves of baseflow according to

$$q_3(t)=q_{30}\exp(-\alpha_{3L}t) \tag{11}$$

where q_{30} is the initial value of q_3.

For the other parameters, the values fitted to the River Ishida basin were used as a first approximation. Only minor modifications were needed for the middle and bottom tanks. However, the parameters of the upper side outlets of these tanks remained undetermined, since the lower side outlets could adequately account for the pertinent runoff components and the water level did not attain H_{2U} or H_{3U} of the River Ishida basin. The required modification of the values of α_1's was more substantial, but the procedure was easy because the value of β_1 needed no modification. Further modification was repeated so that the detailed structure of the hydrographs was reproduced by the model and the error was evenly distributed among the fifteen hydrographs.

The result of the calibration is shown in **Table 1** where it is compared with the result from River Ishida basin. The greatest difference is that the values of α_{2U} and α_{3U} are close to those of α_{1L} and α_{2L}, respectively, in the case of the River Ishida basin. This suggests interaction between the three runoff components due to the flow depth in each soil horizon attaining the thickness of the layer (Takasao et al.[16]). No such phenomena were observed in the River Dart basin, because the rainfall intensity was much smaller than that observed in the River Ishida basin. The differences between two drainage

Table 1. Result of parameter fitting of the cascade tank model to the River Dart and River Ishida basins.

	R. Dart	R. Ishida	
Drainage area	46	23.4	km^2
α_{1U}	0.075	0.2	h^{-1}
H_{1U}	4	35	mm
α_{1M}	0.075	0.1	h^{-1}
H_{1M}	2	12	mm
α_{1L}	0.05	0.025	h^{-1}
H_{1L}	0.5	3	mm
β_1	0.3	0.3	h^{-1}
α_{2U}	0	0.02	h^{-1}
H_{2U}	—	20	mm
α_{2L}	0.025	0.01	h^{-1}
H_{2L}	0	2	mm
β_2	0.03	0.05	h^{-1}
α_{3U}	0	0.01	h^{-1}
H_{3U}	—	20	mm
α_{3L}	0.0084	0.0025	h^{-1}
H_{3L}	0	0	mm
β_3	0	0	h^{-1}

basins in the parameters for the middle and bottom tanks, as shown in **Table 1**, are thought to reflect contrasts in the characteristics of the soil horizons such as permeability, inclination, thickness and length. No further examination of the differences is possible at the present time because the parameters of the tank model have not been related quantitatively to these characteristics of the soil horizon. It is, however, important that a quantitative comparison of runoff characteristics is available when a tank model of the same constitution is applied to different drainage basins.

Because the value of β_1, which largely determines the time constant of the direct runoff, is identical in both drainage basins, the characteristics of the direct runoff can be compared in terms of the rainfall intensity-runoff relationship for hypothetical steady rainfalls as demonstrated in **Fig. 4**. It is seen that the rainfall intensity required to produce a given rate of direct runoff in the River Ishida basin is double that required in the River Dart basin.

The runoff characteristics of the River Dart basin seem similar to those of the River Ishida basin in that the contributing area for the direct runoff is not very variable. According to the theory of the variable contributing area (cf. Hewlett and Hibbert[17)]), runoff coefficient varies with the accumulated rainfall, which is not the case in these basins. The general slope profile in the River Dart basin is convex-concave, as described above, but the concave portion on which saturation overland flow frequently takes place is restricted to a narrow belt along the stream. A similar landscape is commonly found

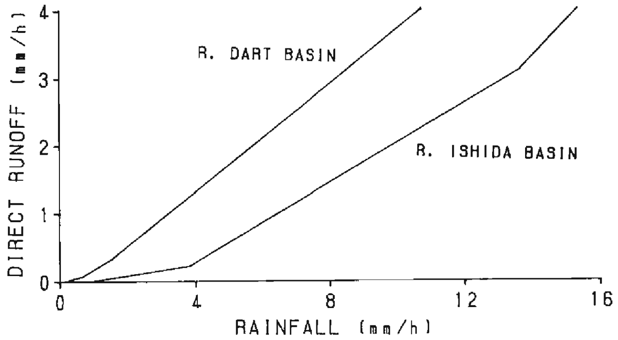

Fig. 4. Comparison of the characteristics of direct runoff between the River Dart and the River Ishida basins.

in the upstream area of the Exe basin.

5. The relationship between the discharge of suspended sediment and direct runoff

Before the correlation analysis was carried out, the calculated values of direct runoff were modified, because the tank model analysis is not perfect and there were minor differences between the observed and calculated hydrographs. One of two possible explanations for these differences is the spatial variability of rainfall intensity which is frequently observed in Southwest England. The other is that a lumped parameter model such as the tank model cannot exactly reproduce extremely transient and non-uniform flow. Therefore, the difference between the observed and calculated hydrographs was attributed to simulation error in the direct runoff except in cases when the throughflow had to be modified to avoid direct runoff becoming negative. Among the fifteen cases analysed, eleven cases in which the required modification was minor were selected for correlation analysis. Typical hydrographs of direct runoff as estimated through the above-mentioned procedure and suspended load are shown in **Fig. 5**.

Because it has been found that most of the suspended sediment transported by the River Dart is derived from erosion of the slope surfaces (Walling and Kane[18]; Peart and Walling[19]), overland flow and return flow, which can be lumped as the direct runoff, are primarily responsible for mobilising the suspended sediment load. Throughflow and base flow contain only very small suspended sediment concentrations. Denoting this concentration as C_{d0}, the sediment load that is produced by the direct runoff Q_{d1} is written as

$$Q_{d1}=C_dQ-C_{d0}(Q-Q_1) \tag{12}$$

where Q is the total stream discharge, Q_1 is the direct runoff, and C_d is the suspended sediment concentration in the stream water. A value of 0.86 mgl^{-1} has been assumed for C_{d0} based on typical values of sediment concentration during periods of stable flow. The

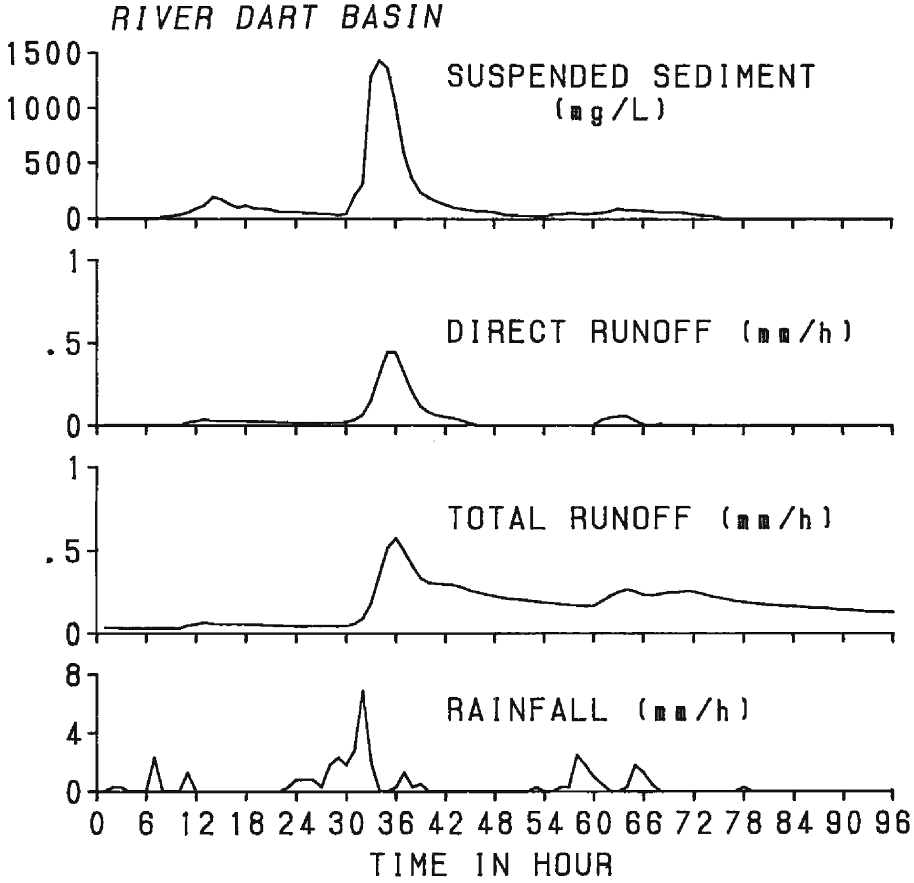

Fig. 5. Concentration of suspended sediment during a storm (the time starting at 00:00, 7 November, 1984).

relationship between Q_{d1} (in gs^{-1}km^{-2}) and Q_1 (in mmh^{-1}) for six rain storms is shown in **Fig. 6**. Because each time series defines a loop, the relationship is not unique. The regression for the interval $Q_1 > 0.18$ mmh^{-1} produces the relationship

$$Q_{d1} = 304\ Q_1^{1.47} \tag{13}$$

The regression for the entire range of Q_1 gives

$$Q_{d1} = 188\ Q_1^{1.11} \tag{14}$$

which means that the concentration in the direct runoff is almost constant. Since the plots exhibit considerable scatter at the interval $Q_1 < 0.18$ mmh^{-1}, Eq. (13) seems more reliable. Examples of the hydrographs of suspended sediment as calculated by Eq. (13) are shown in **Fig. 7**. Although the curves of the calculated load and the calculated concentration are good estimates of the observed curves in general, difference is marked on the rising limb of the hydrograph, especially in the case of sediment concentration. At

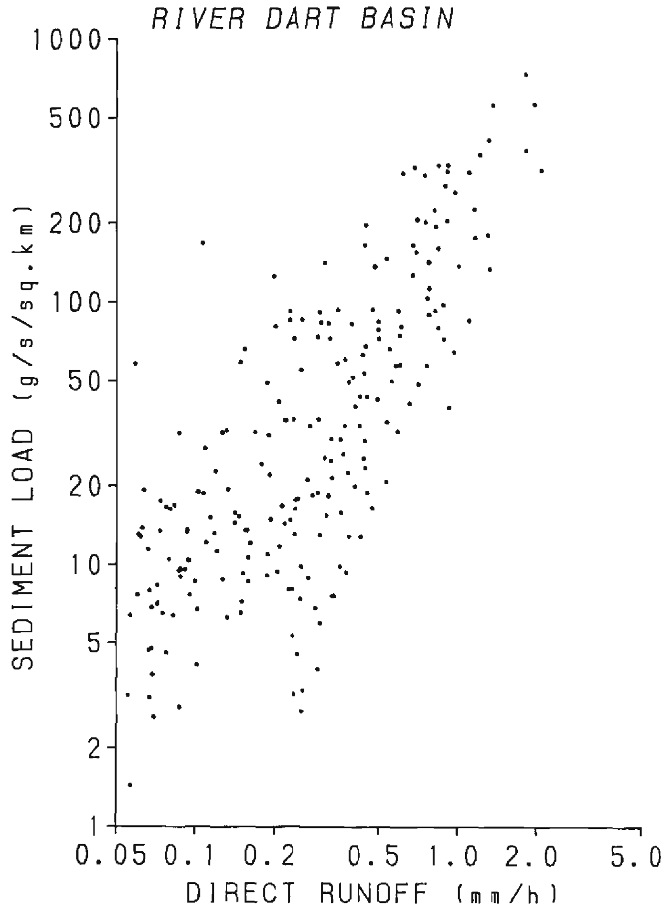

Fig. 6. Correlation between the suspended sediment load and direct runoff (each data point represents the average over one hour).

the time of observed peak concentration, the river discharge is about a half of the peak discharge, which resulted in a great difference in the concentration. It is also evident from **Figs.** 5 and 7 that the suspended sediment hydrograph is not closely analogous to that of direct runoff. **Fig.** 8 shows the time changes of the concentration of suspended sediment in the direct runoff calculated as observed suspended sediment load divided by the direct runoff, for the case of **Fig.** 7. This concentration decreases with time around the peaks of direct runoff. It suggests that if direct runoff rate is constant, the sediment conccentration will decrease with time during a rain storm, presumably because the soil particles which are easily entrained into overland flow are gradually exhausted.

The relationship between the suspended sediment load and stream discharge for the River Ishida basin, which contains no farmland, is shown in **Fig.** 9 based on Okunishi et al.[4]. Although the scatter of the data points might seem less than in the case of the River Dart basin (**Fig.** 6), because the data from fewer rainstorms are plotted, the data

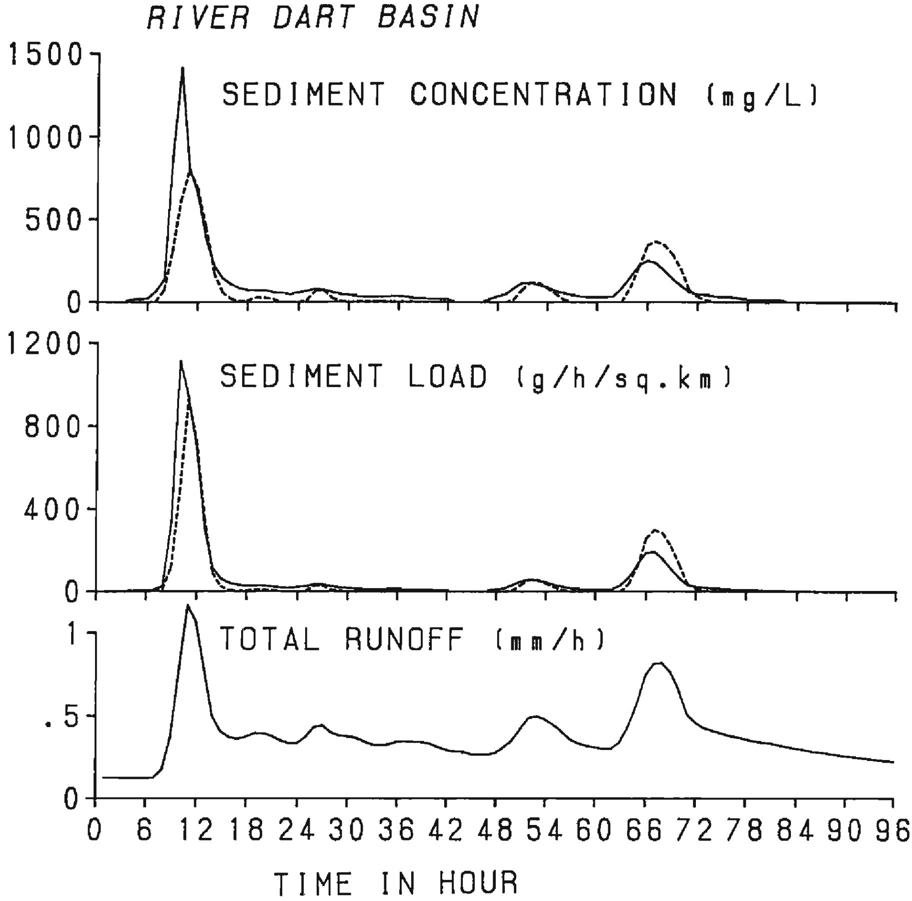

Fig. 7. Sediment concentration (C_d) and sediment load (Q_{d1}) as estimated by Eq. (13) (dashed lines) and as observed (continuous lines). The time starts at 12:00, 9 Decmber, 1982.

representing different seasons define different relationships. It can be suggested that the relationship for the River Dart basin as demonstrated in **Fig. 6** or as analysed by Walling and Webb[20] is more stable than that for the Ishida River basin shown in **Fig. 9** and other relationships obtained in Japanese mountains basins. Data analysis also indicates that the River Dart produces more suspended sediment than River Ishida during moderate rain storms. This suggests that the suspended load mobilised in the River Dart basin derives primarily from the areas of farmland. Detailed experimental studies of small experimental plots on the farmland could provide information on the generation of suspended load that could be examined in terms of sediment hydraulics.

6. The solute loadings of different runoff components

The discharge of dissolved material from the River Dart basin has been observed in

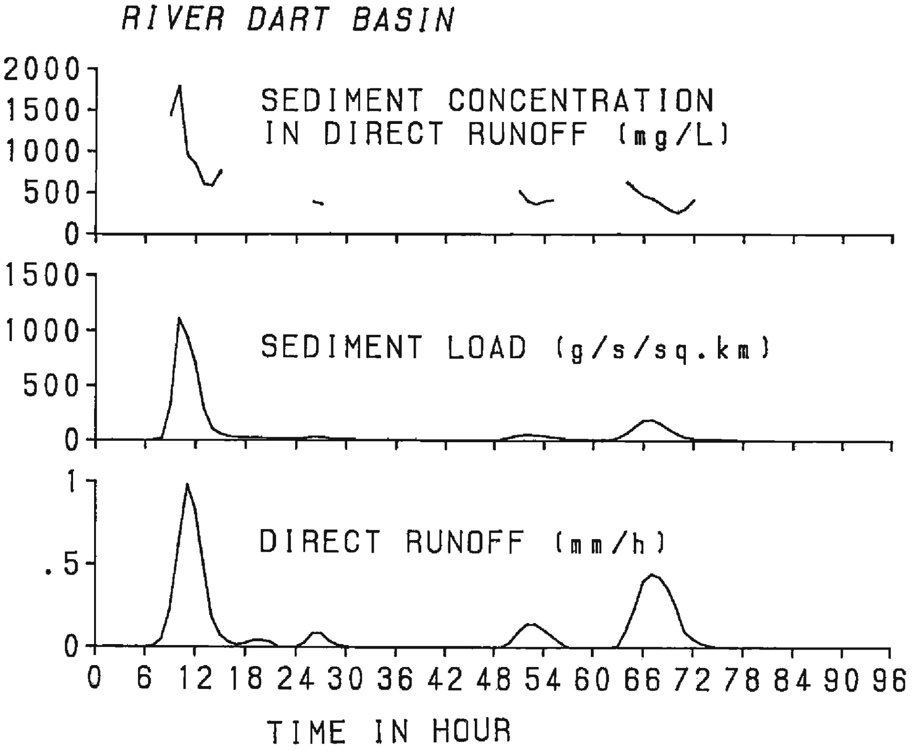

Fig. 8. Sediment concentration in direct runoff (top) calculated as the sediment load (middle) divided by the direct runoff (bottom).

terms of the concentrations of nitrate and magnesium ions in the river water. An example of the data is shown as the continuous line in **Figs. 10** and **11**. The effects of dilution by the direct runoff and throughflow are obvious, but the recovery of nitrate concentration after the peak discharge is greater than that of magnesium concentration. A more sophisticated approach is needed to understand these contrasts.

Multiple regression analysis was carried out under the assumption that each runoff component is characterised by a constant concentration of a particular solute during a rain storm. In other words, the concentration C_i of any solute in the river water may be defined as

$$C_iQ = C_{1i}Q_1 + C_{2i}Q_2 + C_{3i}Q_3 \tag{14}$$

where Q is the total discharge, Q_1, Q_2 and Q_3 are the direct runoff, throughflow and baseflow, respectively, the concentrations in these runoff components $C_{1i} - C_{3i}$ being constant during a rain storm. The results of the regression analysis are shown in **Table 2** and the calculated response is compared with the observed one in **Figs. 10** and **11**.

The calculated concentrations of nitrate and magnesium ions in the river water almost coincide with the observed value in **Fig. 10**, except that the calculated concentrations of both ions are considerably greater when direct runoff and throughflow are

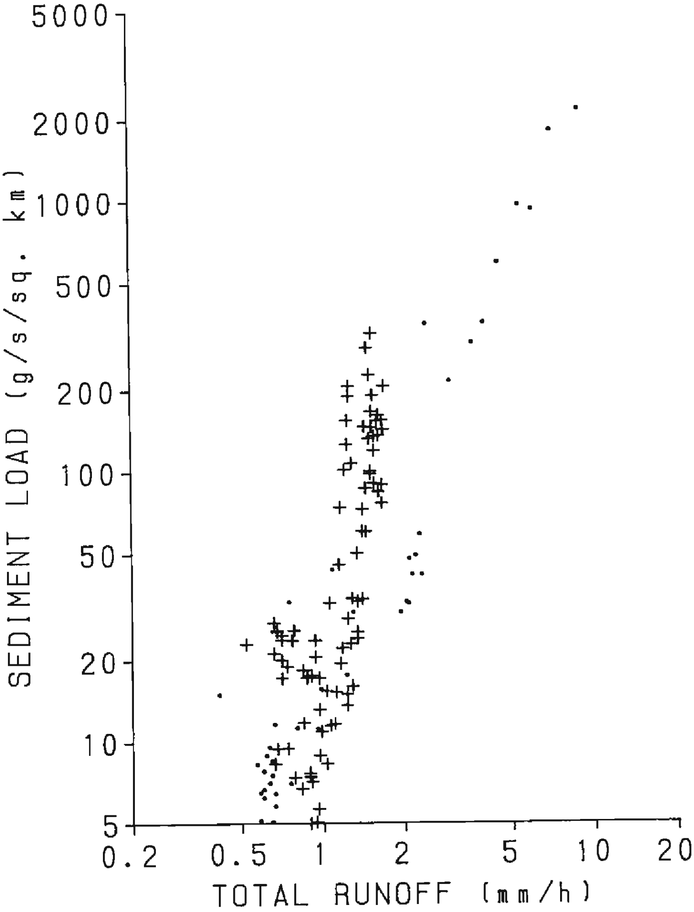

Fig. 9. Correlation between the suspended sediment load and direct runoff for three rain storms in the River Ishida basin ('+' for snowmelt season and '.' for summer).

decreasing. This suggests that the concentration in each runoff component cannot be viewed as completely constant. Discrepancies between the observed and calculated values are more significant in **Fig. 11**. It would appear that the actual concentration of nitrate in the throughflow is initially smaller and then becomes larger than the value provided by the regression analysis. The discrepancy in the interval between 10 and 30 hours can be explained by assuming that the direct runoff during this period consisted of return flow which possessed the hydrochemical properties of throughflow. A marked discrepancy in nitrate concentration in the interval between 74 and 96 hours seems to be caused by a gradual increase of the concentration in the baseflow. It should be noted that the nitrate concentration in the throughflow had to be assumed greater than that in the baseflow in many cases (**Table 2**).

Whereas the magnesium concentrations associated with the different runoff components (**Table 2**) remain fairly constant through the series of storm events investigated,

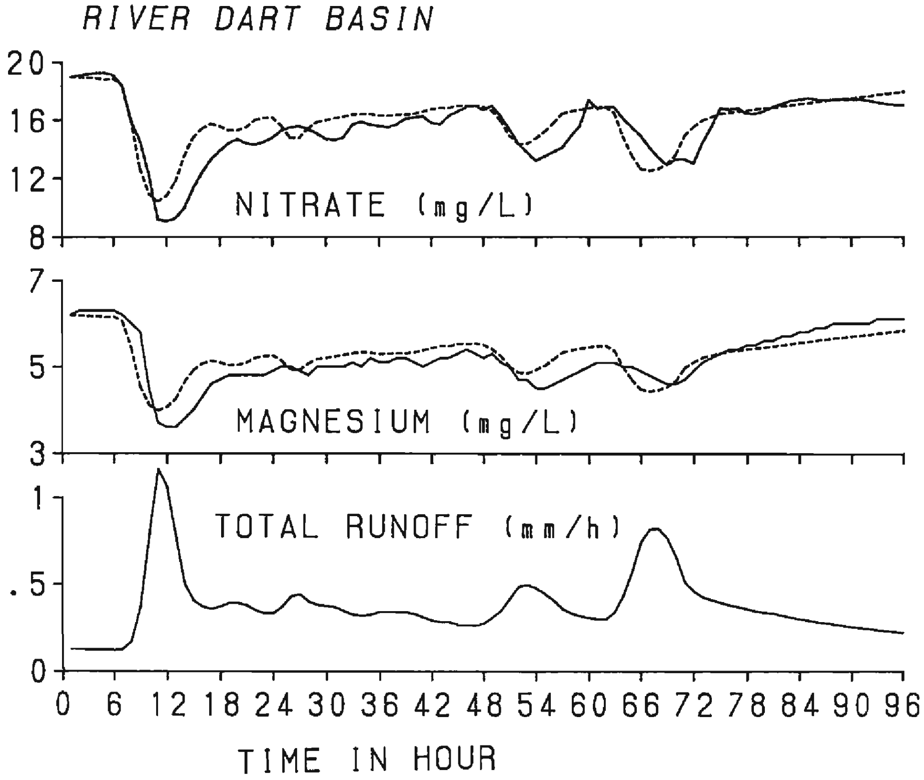

Fig. 10. Calculated (dashed lines) and observed (continuous lines) concentrations of NO_3^- and Mg^{2+} for the rain storm starting at 12:00, 9 December, 1982.

the equivalent nitrate concentrations evidence much greater variability. This variability can be related to seasonal contrasts in nitrate production and availability within the drainage basin which relates partly to fertiliser application and partly to natural controls on mineralisation (cf. Webb and Walling[21)]).

Similar analysis was carried out by Okunishi et al.[4)] concerning different dissolved constituents in the River Ishida basin where the anthropogenic effects on the hydrochemistry are negligible. Some of their results are shown in **Table 3**. In this case the runoff components originating from shallow circulation may have higher concentrations of the ions which originate from rock minerals than those originating from deeper circulation. It is suggested that biological activity in the root zone can be effective in leaching the rock minerals and organic matter.

7. Concluding remarks

The cascade tank model, which was originally devised for small mountainous basins in Japan, proved valid for the River Dart basin without the need for any modification of the fundamental structure. This is because saturation overland flow occurs in limited

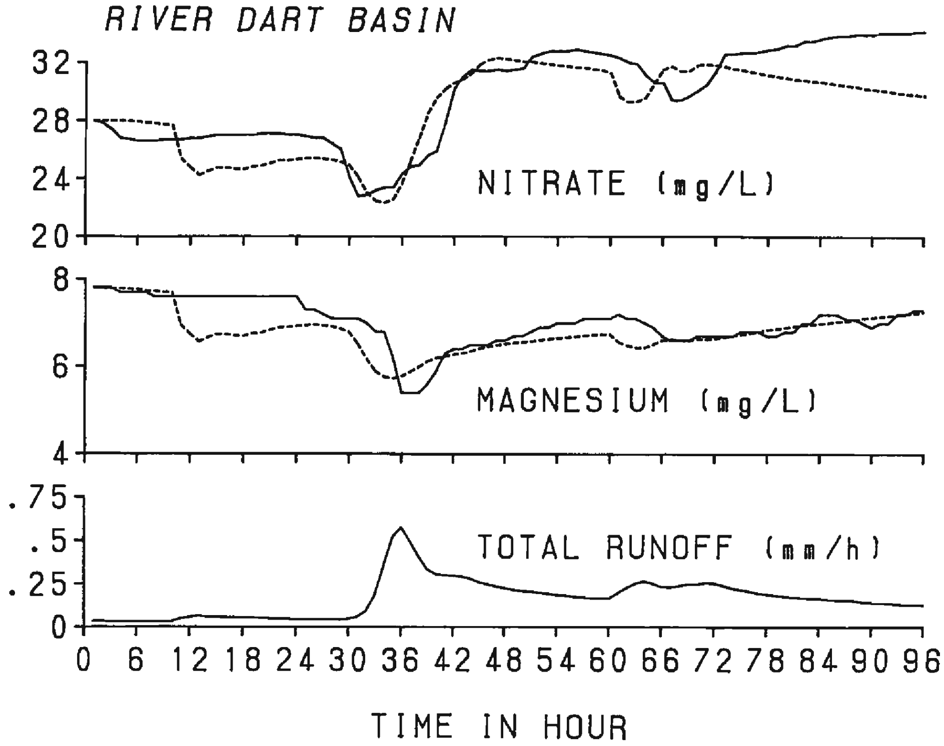

Fig. 11. The same as Fig. 10 but for the rain storm starting at 00:00, 7 November, 1984.

Table 2. The result of multiple regression for estimating the concentration of solutes in different runoff components for the River Dart basin (in mgl^{-1})

Start time of rain storm	Total rainfall	Magnesium			Nitrate		
		C_1	C_2	C_3	C_1	C_2	C_3
14 Mar. 1982	26.3 mm	3.5	4.5	6.4	4.5	9.9	12.7
16 Oct. 1982	24.1	5.5	4.8	6.4	10.5	23.6	17.7
11 Nov. 1982	36.9	3.9	4.7	6.6	9.2	16.6	19.6
9 Dec. 1982	48.3	3.7	4.7	6.2	9.2	14.5	19.0
30 Jan. 1983	43.0	3.0	4.6	6.5	8.8	16.5	14.5
16 May 1983	22.0	4.8	4.9	4.9	8.4	9.5	10.0
20 May 1983	34.3	5.4	3.3	5.1	11.1	6.7	11.0
13 Dec. 1983	32.6	3.4	5.6	6.1	23.6	28.9	28.8
18 Dec. 1983	59.7	4.7	5.5	6.7	21.0	37.0	31.1
5 Feb. 1984	24.8	4.4	6.1	6.4	10.8	20.9	19.3
7 Nov. 1984	37.1	5.6	6.2	7.8	21.1	33.3	28.0
Mean value		4.4	5.0	6.3	12.6	19.8	19.2
Standard deviation		0.9	0.8	0.7	6.0	9.5	6.9

Table 3. The result of multivariate regression for estimating the calcium ion concentration in different runoff components for the River Ishida basin (in mgl^{-1})

Start time of rain storm	Direct runoff	Prompt throughflow	Delayed throughflow	Baseflow
1 Aug. 1982	0.0	1.2	0.0	1.0
23 Mar. 1983	1.9	1.2	0.0	6.5
21 Jul. 1983	3.0	2.4	1.8	1.3

areas near the stream, and it is suggested that the ratio of permeability to peak rainfall intensity is of the same order of magnitude.

The stream discharge record of the River Dart basin was separated into different runoff components by means of the tank model in order to correlate the component discharges with the suspended and dissolved loads during storm events. Since the concentration of suspended sediment in the throughflow and base flow is extremely low and almost constant, excess concentration was attributed to the direct runoff. The correlation between the intensity of direct runoff and the excess suspended load was not so clearly defined as to explain the peak sediment concentration satisfactorily. However, a possible mechanism of producing suspended sediment during storm events was proposed based on a comparison between the observed and calculated concentrations of suspended sediment. Future studies of suspended sediment production should be based on the hydraulics of overland flow in specific parts of the basin.

Analysis of the dissolved loads associated with different runoff components was undertaken using data on the concentration of magnesium and nitrate ions in the stream water and assuming a constant concentration in each runoff component. The magnesium ion, a material which is typically produced by rock-water chemical interaction, was found to occur in each runoff component with an essentially constant concentration. On the other hand, nitrate ion concentrations, which reflect biological and anthropogenic activities, demonstrated a rather different behaviour. Concentrations in the river water varied markedly from season to season and through the year. Furthermore, the concentrations in the individual runoff components varied considerably during storm events in response to transient mineralisation and leaching of nitrate ions. More intensive analysis of this phenomenon would elucidate the environmental buffer action of the ecosystem.

Acknowledgements

The authors are grateful to Dr. B. W. Webb, University of Exeter, for helpful discussion. This research was carried out when one of the authors (Okunishi) stayed at the University of Exeter under the financial support of the Japanese Ministry of Education to carry out research works with another author (Walling).

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